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DETERMINATION OF ALLOW. ABLE FLOWS

Final Report
Determination of Allowable Flows

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Background

The transport of sediment by water is a primary modifier of the landscape. Transport of sediment in stream and river channels sets the form and function of the channels far into the future. If an imbalance exists between the transporting power of the flowing water and the sediment in the channel, the shape and form of the channel can be adversely changed to the point that the channel can no longer sustain itself and a different channel form results.

Diversions of water from channels can significantly reduce the sediment transporting power or capacity of the channel (for example see Parker et al., undated). If that occurs, then the channel may begin to aggrade and change shape. If the water is diverted during the flows that maintain the channel shape and function, the so-called channel maintenance flows (USDA Forest Service, 1997), then the effect may be even more pronounced. The question arises as to how much and when can water be diverted from a channel so that the transport capacity of a stream is not significantly affected. Therefore, the purpose of this study was to determine the amount of flow that can be diverted during the channel maintenance flow regime for various gravel-bed snow melt driven stream systems without substantially altering gravel transport. The goal of this study was to develop an equation set or nomograph that predicts the level of flow allowable for various channel configurations of width, depth, slope and roughness.

Scope of Work and Objectives

The scope of work for this study consisted of three basic elements, which were:

1. Develop a study plan that describes the approaches to be used and a timetable (submitted earlier).
2. Conduct the necessary scientific investigations.
3. Prepare a completion (final) report that describes methods for determining what flows can be diverted without detectable altering of gravel transport.

The objectives for the study were more extensive and were submitted in the study plan. The objectives for the study included:

1. Select, in consultation with the USDA Forest Service, appropriate equations or calculation approaches applicable to sediment transport in gravel-bed streams. The equations or approaches will include those developed by Parker and Yang. The approaches will also include linear and/or non-linear models of sediment transport rate and water discharge developed via regression analyses of data supplied by the USDA Forest Service.

2. Prepare a list of necessary data on snow-fed gravel-bed streams and collect the relevant information from the USDA Forest Service. These data will include the following types:
   a. channel characteristics information of cross-section measurements; bed slope; resistance to flow; and flow depths, top widths, and average velocities at various discharges (this was anticipated to be at the bed load transport measurement site if the cross section at that site is representative of the channel reach, if not than information from a set of cross sections should be obtained),
   b. sediment characteristics of bed material size distribution and how it was collected; bed load transport rates and corresponding water discharge rates; type of bed load sampling device used at the site; distribution of sizes caught in the sampling device including maximum size caught; and,
   c. discharge characteristics of annual peak flows and a representative snow melt runoff record with the following attributes - hourly increments (discharge or stage with conversion equation), flow ranges from 0.8 of the 1.5 year return period discharge to at least the 10 year return period discharge, and a period of no more than 60 days.

   The data shall be supplied by the USDA Forest Service for two sites, East St. Louis Creek and Little Granite Creek.

3. Combine the information on channel characteristics, sediment characteristics, discharge characteristics with the sediment transport equations (approaches) in such a manner as to create a set of design equations or nomographs. The planned approach to the data analyses and synthesis is as follows.

a. Determine the characteristics of a representative channel cross at each site to include relationships between hydraulic characteristics between discharge, top width, flow area, average velocity and flow resistance, as applicable. These analyses will require linear and/or non-linear modeling of the data. Develop a set of relationships that can be used to estimate parameters, such as depth of flow, needed for the sediment transport equations and for other dimensionless ratios such as width to depth.
b. Determine the "bank full" discharge at the sites based on the 1.5 year return period (67% exceedence) peak flow as computed from a Log-Pearson Type III distribution analysis of the peak flow data. The procedures detailed in Bulletin 17B will be applied unless otherwise agreed. The 1.5 year return period flow will be used as the normalizing value for the "0.8 bank full" discharge and other discharge rates.
c. Develop a representative snowmelt runoff hydrograph from the data, on hourly increments, for a period not to exceed 60 days. This may require analyses of stage recordings. Peak daily flows should be retained in the record and not averaged over the hour in which they occur.
d. Develop, using linear regression and/or non-linear modeling, the relationship between bed load transport rate and water discharge. This can be done in Microsoft Excel or in SAS for Windows.
e. Use the transport-flow rate relationship developed above to estimate the sensitivity of the transport rate to changes in flow rate. This will be done through a set of numerical analyses of the derivative of the equation; a confidence interval analyses based on the parameters of the equation; a simulation of sediment yields based on the representative hydrograph developed in Objective 3c (using flow rates on one hour, one day and one week time scales); and a Monte Carlo simulation to create a data set of realizations for further statistical analyses. This last approach will entail simulations that add a random component to the estimated value (of flow and/or of predicted transport rate) in order to ascertain the variance of the transport rate estimates.
f. Apply the Parker and Yang bed load transport equations (approaches) to the data set at the two sites. Compare the results (transport estimates) with the measured data and with the results from the linear and/or non-linear transport equation.
g. Determine, by comparing the analyses at the two sites, if a universal or non-dimensional approach can be developed to estimate the effects of reduced flow on the sediment transport and whether those effects are "significant". This will require some judgment of what is "significant" given the variability in the estimates as delineated in Objective 3e.

4. Submit a draft report for review to the USDA Forest Service. The draft report will include a detailed methodology, the work products from the objectives (including electronic form), conclusions as to the applicability of such a universal approach, and recommendations for further study. The draft report will also include a discussion on the level of confidence or scope of interference that is appropriate for the small (two stream) sample size under consideration.

Approaches, Data and Other Information

Transport Equations

The two types of transport equations that were considered in this study were those presented by Parker and Klingeman (1982) (and modified by others, e.g., Bakke, et al. (1999)) and by Yang (1984). These are referred to respectively as the P-K and Yang methods. Both of these methods/models were developed for the estimation of bed-load transport.

Parker-Klingeman Method

Weinhold (2001) applied the P-K method to two streams, one of which is considered in this study. That stream, Little Granite Creek in Wyoming, will be described in a subsequent section. The P-K method was founded on data from Oak Creek in Oregon. The key assumption in the method is that the bed of the stream develops a coarse layer (gravel sized and larger materials) that defines the interchange between bed material in the stream and the bed load transport in the flowing water. The interchange is also affected by the concept of equal mobility. Parker and Toro-Escobar (undated) contend that there are two forms of the concept. In the draft manuscript, the authors hold that the weak form of the concept "states that in order to transport the coarse half of the mean annual gravel load through a river reach at a rate equal to the fine half, the coarser materials must be overrepresented on the bed surface, giving rise to a mobile-bed armor." As the bed shear stress increases, the degree of mobile-bed armoring needed to fulfill the weak concept is decreased. In contrast, the strong form of the concept "states that the grain size distribution of the gravel portion of the bedload should be similar to that of the substrate and finer than that of the surface layer." Parker and Toro-Escobar cite Lisle (1995) to demonstrate that although many streams satisfy the strong form of the equal mobility concept, but many others do not and these tend to be smaller streams in the upland portion of watersheds. In a flume experiment conducted to test the two concepts, it was found that both concepts were supported by the results. This study suggests the importance of measuring the surface and substrate (subsurface) materials in order to more accurately model the bed load transport.

Attendant to the equal mobility concept is the concept of hiding factor. In this concept, smaller particles "hide" behind the larger particles thus requiring more shear stress to initiate transport. In the P-K method, the hiding factor is represented through a reference shear stress as

$$\tau^*_{ri} = \tau^*_{r50} (D_i/D_{50})^{-exp} \qquad (1)$$

where τ^*_{ri} is the reference Shields stress only slightly above the critical values of that needed for particle size class i, D_i is the representative particle diameter of size class i, D_{50} is the median particle diameter for the bed material (surface or substrate, depending

on what one is modeling), τ^*_{r50} is the reference Shields stress for the D_{50} particle, and exp is an exponent designated in the P-K method. Bakke et al. (1999) show that the exp value for the original Oak Creek data was 0.982 and that the values for seven streams in the Klamath River basin of Oregon ranged from 0.907 to 0.974. Weinhold (2001) reported that the overall (all data) exp values for the two streams in his study, Little Granite Creek and the South Fork of the Cache La Poudre, CO, were found from optimization (using the methods of Bakke et al. 1999) to be 0.973 and 0.926, respectively. Other authors have found values of exp to range from 0.7 (unequal mobility) to about unity. Although Bakke et al. (1999) did not report on the optimized values of τ^*_{r50} for the Klamath River basin streams, Weinhold reports the τ^*_{r50} values were found to vary with discharge, Q, with the form

$$\tau^*_{r50} = a\, Q^b \qquad (2)$$

where Q is water discharge through the measurement section in cubic feet per second (cfs) and a and b are regression parameters. Because the model used by Weinhold (SEDCOMP, see also Bakke et al., 2001) to optimize τ^*_{r50} and exp did so for a discretized cross section at each discharge Q, it was possible to relate τ^*_{r50} to Q. For the 11 years of record at Little Granite Creek, the a parameter varied from 0.0575 to 0.1537 and that the b parameter varied from 0.158 to 0.332 when each sampling year was optimized separately. The overall a and b parameters for all 11 years were 0.0680 and 0.302, respectively. At the South Fork Cache La Poudre site for two years of data collection, the a parameter was found to be either 0.0851 or 0.1621 and the b parameter was found to be 0.171 or 0.057, depending on the year for all the data at the South Fork of the Cache La Poudre, the a and b parameters were found to be 0.0971 and 0.144, respectively. These results show the variability of the parameters. However, it may be useful to note that the a and b parameters, because they are derived form the same data sets, are necessarily related to one another. In this case, they are inversely related as shown in Figure 1.

As a comparison, the value of τ^*_{r50} at the Oak Creek site was a constant or 0.0876. Bakke et al. (1999) have observed that although τ^*_{r50} and exp both have effects on bed load transport, τ^*_{r50} has a greater influence on the total quantity, whereas the exp affects the size distribution of the bed load. The relationships found by Weinhold are intriguing and should be explored at other sites where the P-K method is optimized. It is also worth noting that the overall b parameter in equation (2) for Little Granite Creek is almost exactly the same exponent as found for depth as a function of discharge (as will be shown in equation (13) in a following section). Shear stress is related to depth, so perhaps this is another area to explore.

The specific aspects of the P-K model are described in the following paragraphs as extracted from Bakke et al. (1999) and Weinhold (2001). The site-specific hiding factor relationship (equation (1)) is used in the P-K model as part of the normalized Shields stress, Φ_i, or

$$\Phi_i = \tau^*_i / \tau^*_{ri} \qquad (3)$$

where τ^*_i is the dimensionless Shields stress for a particle of size class i. It is defined as

$$\tau^*_i = \tau/((\gamma_s - \gamma)\, D_i) \qquad (4)$$

where $\tau = \gamma dS$ or the local bed shear stress at the point of interest, γ_s is the unit weight of the sediment (typically 2.6 to 2.7 grams per cubic centimeter), γ is the unit weight of water (such as 1 gram per cubic centimeter), d is the local depth of water at point of interest, S is the energy slope of the flowing water, and D_i is the representative diameter of the sediment particle of interest. Because equation (4) is to yield a dimensionless value, the parameters in the equation must have consistent units.

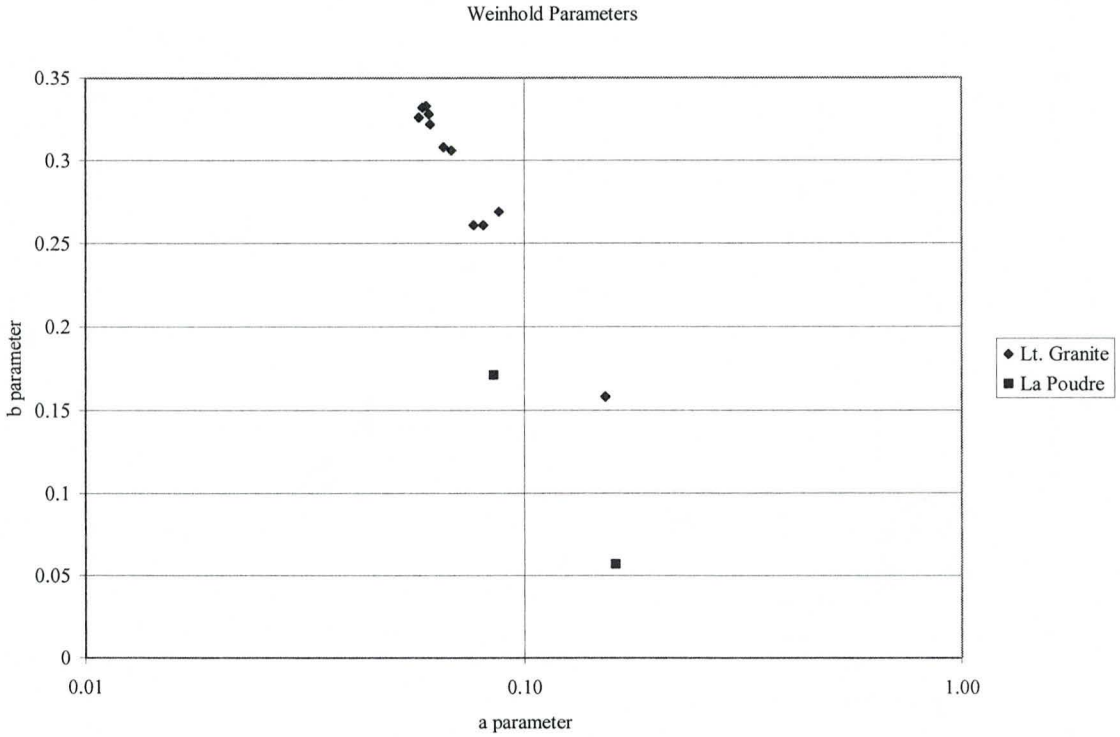

Figure 1. Relationship between a and b parameters in the equation $\tau^*_{r50} = a\, Q^b$ (data from Weinhold, 2001)

The dimensionless bed load transport rate ratio, G, was defined by Parker and Klingeman (1982) as

$$G = W^*_i / W^*_{ref} \qquad (5)$$

where W^*i is a dimensionless bed load transport rate for size class i and W^*_{ref} is a reference dimensionless bed load transport rate chosen to represent a small but measurable rate ($W^*_{ref} = 0.002$). The variable W^*_i is the dimensionless bed load transport rate for size class i defined as

$$W^*_i = (s_g\text{-}1) q_{bvi} / (f_i\, g^{1/2} (dS)^{3/2}) \qquad (6)$$

where s_g is the specific gravity of sediment particles ($= \gamma_s/\gamma$), q_{bvi} is volumetric bed load transport rate per unit width of computational section in size class i, f_i is fraction of bed material (pavement or sub-pavement) in size class i, g is the acceleration of gravity, and d and S were defined above.

These parameter definitions allowed the measured data to be fit with a single curve, which is the bed load transport function of

$$G = 5.6 \text{ X } 10^3 \, [1 - (0.853/\Phi_i)]^{4.5} \qquad (7)$$

Equation (7), when used in conjunction with equations (2), (3) and (5), comprises the P-K bed load transport model (Parker and Klingeman, 1982). A more useful form can be found by rearranging the above equations to yield the weight sediment transport rate per unit width in size class i, q_{bwi}, as

$$q_{bwi} = [f_i \, g^{1/2} \, (dS)^{3/2}] W^*_{ref} \, G \, [\gamma \, s_g / (s_g - 1)] \qquad (8)$$

Unit transport rates are then multiplied by their local width increment and summed across the channel cross section to yield a total bed load transport rate by size class. Equation (8) contains the hiding factor relationship discussed above, thus allowing site calibration of the P-K model to local conditions as was done by Bakke et al. (1999) and Weinhold (2001). An operational version of the P-K model (SEDCOMP) was graciously provided to the author by David Dawdy (personnel communication).

Yang Method

Yang (1984) proposed a regression equation based on flume data for estimating gravel bed load. He developed the equation around the concept of dimensionless unit stream power and then fit the parameters of the equation via multiple regression analysis of the data sets he had collated (see Yang, 1972; Yang, 1973; and Yang and Molinas; 1982, for a chronology of the method). Unit stream power is defined as the product of average flow velocity, V, and energy slope, S, of the flowing water. The dimensionless unit stream power is the unit stream power divided by the average fall velocity, ω, of the sediment particles. Yang's model for gravel transport is

$$\text{Log } C_{tg} = 6.681 - 0.633 \log(\omega D/\nu) - 4.816 \log(U_*/\omega)$$

$$+ [2.784 - 0.305 \log(\omega D/\nu) - 0.282 \log(U_*/\omega)] \log [(VS/\omega) - (V_{cr}S/\omega)] \qquad (9)$$

where log is log base 10, C_{tg} is the total gravel concentration in parts by weight, D is the median particle diameter, ν is the kinematic viscosity of water, $U_* = (gRS)^{1/2}$ or the shear velocity (which is equivalent to $[\tau/\rho]^{1/2}$), R is the hydraulic radius of the channel (equal to d, the depth, at a point in the channel), and V_{cr} is the critical velocity at which movement begins. The dimensionless critical, V_{cr}/ω, can be found as

$$V_{cr}/\omega = [2.5/(\log (U_*D/\nu) - 0.06)] + 0.66 \qquad \text{if } 1.2 < (U_*D/\nu) < 70, \text{ or}$$

$$V_{cr}/\omega = 2.05 \qquad \text{if } (U_*D/\nu) \geq 70 \qquad (10)$$

The fall velocity for particles larger than 0.062 mm can be estimated by a formula developed by Rubey (Simons and Senturk, 1976) as

$$\omega = [[2/3\ g\ (s_g - 1)\ D^3 + 36v^2]^{1/2} - 6v]/D \qquad (11)$$

Note that water has a kinematic viscosity of 1.02×10^{-6} m^2/sec at a temperature of 20°C, and increases to 1.75×10^{-6} m^2/sec at a temperature of 0°C (Mott, 1972). This variation in viscosity is negligible and for particles with diameters in the range of gravel, i.e., 2 to 64 mm, omitting viscosity creates an error that is less than 2% (for the 2mm size, and less error as the size increases). The velocities computed from equation (11) are consistent with those shown in graphs in ASCE (1977).

These two methods, the Parker-Klingeman and Yang, are applied to the data sets provided by the USDA Forest Service. For more information on bed load equations, the reader is directed to Lopes et al. (2001) and Habersack and Laronne (2002) both of which compare selected bed load equations, including the P-K method.

Data

The data used in this study were supplied by the USDA Forest Service. Two locations were selected for investigation. These were Little Granite Creek in Wyoming and East St. Louis Creek in Colorado. Both streams are characterized by snow melt runoff. The Little Granite Creek information has been described by Weinhold (2000) and by Ryan and Emmett (2002). For this study, a pre-publication review manuscript for the Ryan and Emmett General Technical Report (GTR) was provided by the USDA Forest Service.

Little Granite Creek

Little Granite Creek is a tributary of the Snake River south of Jackson in western Wyoming. The watershed area is about 54.7 km^2 (21.1 square miles) and drains generally to the south. Elevations range from 1948 to 3340 meters. The channel at the sampling section is a bit less than 10 meters wide. The mean low-flow water surface slope is about 0.02. Bed material in the channel is primarily gravel and small boulders, with a distinct difference between the size characteristics of the surface and subsurface materials. The data set was supplemented with peak and daily discharge information from the USGS Water Information System. The period of available record was 11 December 1981 through 31 October 1992. The seasonal (April through September) water yield for the eleven seasons in the record was 17.86 inches (0.454 m). The average daily flow for the season was 55.4 cfs (1.57 cubic meters per second), and the average daily discharge for the entire record was 31.4 cfs (0.89 cms)

Peak discharge data were analyzed to determine the 1.5-year (0.67 chance of exceedence) return flow using a log-Pearson Type III analysis (USWRC, 1981). The 1.5-year return flow peak discharge is believed to correspond to the bank full discharge in a stream. The results were similar to those presented by Ryan and Emmett (2002). Their estimate was 210 cfs (5.95 cms) while that found for this study was 212 cfs (6.01 cms). In this study, a different value for the May 8, 1992, peak flow was used in the procedure. Although

Ryan and Emmett (2002) used 93 cfs (an estimate equal to the average daily flow for that day), in this study relationships between peak and average daily flow for the days before, of, and after the peak, were used to estimate the peak as 109 cfs. This slight difference caused very little difference in the estimates. The variability of the estimated 1.5-year peak flow discharge was extreme as noted by Ryan and Emmett. The variability in the estimate is influenced by the short 11-year record at the site. Although a record of average daily discharges was obtained from the USGS web site, no data were found or provided for the diurnal variation of the discharge, i.e., within a day.

Weinhold (personnel communication) supplied the tabular information from the Ryan and Emmett GTR (2002) in electronic form. Data were listed for the period 1981 through 1992 and for 1997, i.e., 13 years. From those data, relationships were found between discharge, depth, width and velocity for the site. All the data observations, 142 as supplied in the electronic file plus an additional 14 from the draft manuscript, were used to relate the channel hydraulic characteristics to discharge. The relationship for each were found to be

$$w = 11.808\ Q^{0.191} \qquad (R^2 = 0.837) \qquad (12)$$

$$d = 0.273\ Q^{0.308} \qquad (R^2 = 0.872) \qquad (13)$$

$$v = 0.309\ Q^{0.506} \qquad (R^2 = 0.964) \qquad (14)$$

where the width, w, and depth, d, are in feet; the average velocity, v, is in feet per second; and discharge, Q, is in cfs. The coefficients and exponents in equations 12 to 14 are consistent with those presented by Ryan and Emmett (2002). Note that the exponents on equations 12 to 14 should (theoretically) add to 1.0 and the coefficients should multiple together to equal 1.0. Ryan and Emmett (2002) used a reduced data set of 151 observations for their relationships thus causing some of the difference between the results. The R^2 values for equations 12 to 14 are based on the log base 10 transformed values of the dependant variables and of Q.

Bed material samples were reported by Ryan and Emmett for pebble counts and manual removal of surface and subsurface (substrate) materials. The pebble counts were conducted in 1994, 1997 and 2000 with D_{50} sizes ranging from 55 to 89 mm. "Barrel" samples were collected in 2000 from the surface and subsurface. The D_{50} sizes for the surface ranged from 35 to 67 mm and for the subsurface, 10 to 21 mm. The pebble count D_{84} sizes were significantly larger than the barrel samples.

Bed load transport measurements for the site were collected from the same periods, 1982 through 1992 and 1997, as the hydraulic geometry data. The electronic data supplied by Weinhold contained 280 observations of discharge and bed load measurements and 169 observations of discharge and suspended sediment transport.

The bed and suspended load transport data sets were analyzed and fit to equations of the form:

$$Qs = aQ^b \qquad (15)$$

where Qs = sediment transport rate (usually in mass per time) and Q = water discharge rate (usually in volume [or mass of water] per time). The parameters a and b were fitted by least-squares regression resulting in

$$Q_b = 9.45 \times 10^{-7} Q^{2.89} \qquad (R^2 = 0.719) \qquad (16)$$

$$Q_s = 0.0127 Q^{1.59} \qquad (R^2 = 0.819) \qquad (17)$$

where Q_b and Q_s are bed and suspended loads, respectively, in tons per day and Q is water discharge in cfs. The parameters in equations (16) and (17) are identical to those found by Ryan and Emmett (2002), considering any rounding of digits. The correlation coefficients are based on the log-transformed values, as elsewhere in this report.

East St. Louis Creek

The East St. Louis Creek (abbreviated as ESLC) is located in the USDA Forest Service Fraser Experimental Forest in north central Colorado. St. Louis Creek proper is a northeast flowing tributary to the Fraser River. Peak elevations on the watershed boundary reach 3903 meters. The watershed area for the ESLC is 8.03 km^2 (3.1 square miles). The bank full width is 2.9 meters and the water surface slope is approximately 0.055. Data relevant to this study were collected for four seasons and supplied by the USDA Forest Service.

Peak flow data for ESLC was provided for the years 1943 through 1998, 56 years. The data were analyzed to determine the 1.5-year (0.67 chance of exceedence) return flow using a log-Pearson Type III analysis. The estimated 1.5-year (bank full) flow is 26.6 cfs (0.753 cms). This value is close to that provided by the USDA Forest Service in draft manuscript materials, 26.5 cfs (0.75 cms). The maximum peak flow recorded at the site was 65.91 cfs (1.87 cms) in 1957, and the average seasonal (April through September) water yield is about 14.04 inches (0.357 m). The average seasonal daily discharge was 7.48 cfs (0.212 cms).

The USDA Forest Service supplied bed load sampling data for the four collection seasons, 1993 and 1995 through 1997. The collection seasons were centered on the month of June with start dates as early as May and end dates into July. There were a total of 109 observations in the data base. Ninety-nine (99) of these had usable bed load information. The 109 observations were analyzed for relationships between discharge, and channel width, depth and velocity. The power relationships developed from the data are

$$w = 9.360 Q^{0.0097} \qquad (R^2 = 0.229) \qquad (18)$$

$$d = 0.300 Q^{0.354} \qquad (R^2 = 0.749) \qquad (19)$$

$$v = 0.362 Q^{0.634} \qquad (R^2 = 0.894) \qquad (20)$$

where the width, w, and depth, d, are in feet; the average velocity, v, is in feet per second; and discharge, Q, is in cfs. The relationship between width and discharge is poor because

the bank full width at the section is constrained to about 2.9 meters (9.5 feet). Cross-sectional data supplied by the USDA Forest Service show the entire channel width was more on the order of 6 to 7 meters.

Bed material data for the site show that the D_{50} was 50 mm and that the D_{84} was about 151 mm. About 3 percent of the material was finer than gravel size (less than 2 mm) and about 42 percent was larger than gravel size (greater than 64mm).

The 99 observations of bed load data were analyzed and a power equation was developed as

$$Q_b = 9.203 \times 10^{-5} Q^{2.68} \qquad (R^2 = 0.492) \qquad (21)$$

where Q_b is in tons per day and Q is in cfs. The relationship has a marginal correlation coefficient. Transport information for suspended sediments was not provided in the data sets for ESLC.

Comparisons between Selected Sites

Table 1 shows a comparison between parameters developed for this study at the two sites, Little Granite Creek and East St. Louis Creek. The normalized, by channel width, Q_b relation is listed in Table 1 as a comparison. Because the width at the ESLC site is fairly constant with discharge, the exponent remains about the same. In contrast, the exponent on the width normalized Q_b at the Little Granite Creek site changes from 2.89 to 3.27

Table 1. Selected Parameters for Study Sites

Parameter	Little Granite Creek	East St. Louis Creek
Area, square miles	21.1	3.1
Seasonal Runoff, inches	17.86	14.04
Q_{100} peak flow, cfs/mi^2	70.85	21.39
Q_{25} peak flow, cfs/mi^2	47.16	18.35
Q_{10} peak flow, cfs/mi^2	33.87	16.00
$Q_{1.5}$ peak flow, cfs/mi^2	10.05	8.58
D_{16} of surface material, mm	24 (Yr. 2000 pebble count)	14
D_{50} of surface material, mm	89 (Yr. 2000 pebble count)	50
D_{84} of surface material, mm	208 (Yr. 2000 pebble count)	151
Water surface slope, ft/ft	0.020	0.055
Width = f(Q)	$11.808\ Q^{0.191}$	$9.360\ Q^{0.0097}$
Depth = f(Q)	$0.273\ Q^{0.308}$	$0.300\ Q^{0.354}$
Velocity = f(Q)	$0.309\ Q^{0.506}$	$0.362\ Q^{0.634}$
Q_b = f(Q), t/day	$9.45 \times 10^{-7}\ Q^{2.89}$	$9.203 \times 10^{-5}\ Q^{2.68}$
Q_s = f(Q), t/day	$0.0127\ Q^{1.59}$	No Data
Q_b = f(Q/width), kg/s/m = f(cms/m)	$0.027\ Q^{3.27}$	$0.084\ Q^{2.69}$

once the varying width is introduced. If a normalizing discharge, such as 0.8 of bank full, is used, the exponents do not change. The coefficients change when a normalizing factor is introduced.

Hydrograph Data

Although average daily discharge data were obtained from the USGS web site for Little Granite Creek and seasonal water yields were for ESLC were supplied by the USDA Forest Service, no records or information on diurnal flow variation was supplied to the study or found through usual sources. However, the diurnal flow variation is not critical to the outcome of this study as will be evident.

Diversion Effects – Bed Load Equation Sensitivity

The easiest way to determine the direct affect on bed load transport caused by reduced discharge is to examine bed load equations such as equation (15). If equation (15) is linearized as

$$\text{Ln}\,(Q_s) = \text{Ln}\,(a) + b\,\text{Ln}\,(Q) \qquad (22)$$

where Ln is the natural logarithm function, then differentiation of equation (22) yields

$$dQ_s/Q_s = b\,dQ/Q \qquad (23)$$

The terms dQ_s/Q_s and dQ/Q can be interpreted as the relative change of the variable, such as a 0.05 or 5% change in the water discharge rate. For example, using the "b" value from equation (16), the effect of a 5% change in the water discharge would be a 14.4% (= 2.89 x 5%) change in bed load transport. Similarly, a 5% change in discharge would affect the suspended sediment transport by about 8% (see equation (17)). These analytical results were verified numerically by using the entire average daily flow record for the USGS gauging site on Little Granite Creek as a base set of data. The average daily flow was converted, using equations (16) and (17), to sediment transport rates. The flow rates were then varied by fractional changes of +/- 20%, a reasonable range in discharge measurement errors. A sensitivity plot (Figure 2) demonstrates that the slopes of the lines for bed and suspended loads do match the corresponding "b" values of 2.89 and 1.59, respectively.

This simple demonstration shows the effect of changes in flow on sediment transport. At many other locations, the b parameter is greater than 1.0, which implies an amplification effect on Qs with a change in Q. Weinhold (2001) reproduced the bed load rating curve using P-K method. This implies that the P-K estimated transport is similarly as sensitive to variations in flow as is the rating curve.

The effects in the variability of the flow were also examined through computations of the total loads, bed and suspended, for the entire flow period on record. This can be demonstrated by: a) summing the estimated daily loads based on the individual daily

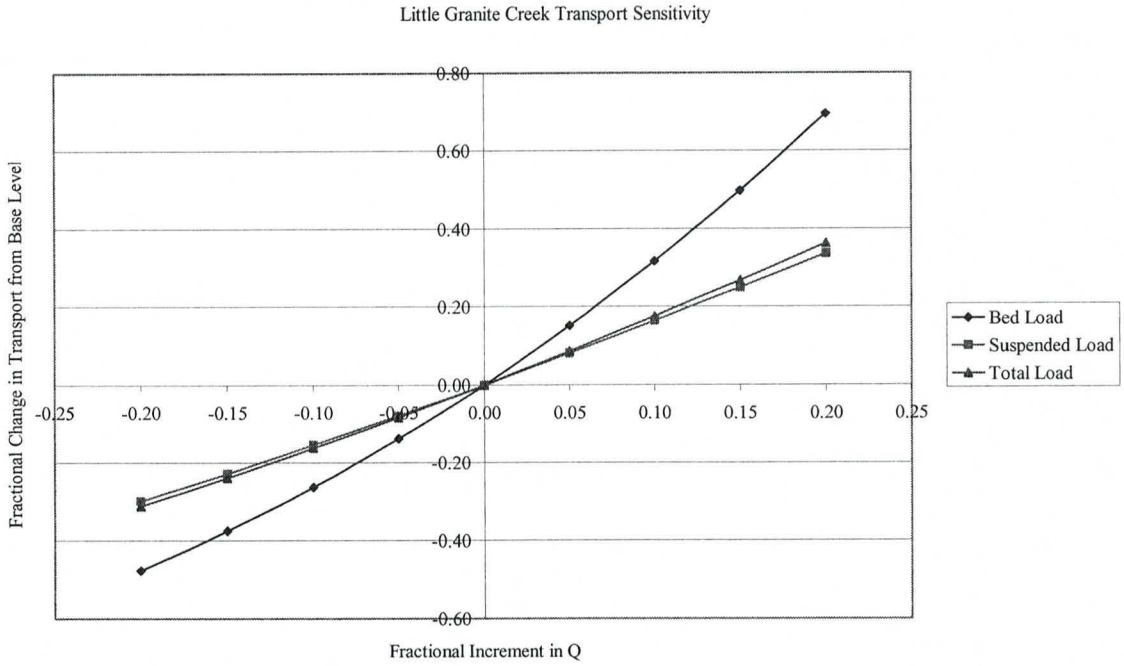

Figure 2. Sensitivity of Sediment Transport to Changes in Discharge Rate, Little Granite Creek

discharges and comparing that to b) calculating the average daily discharge and using that value to find the average daily load. Because the exponent in equation (15) is 2.89, a large difference is expected. If the exponent were 1.0, there would be no difference between the computations. The average of the estimated daily loads, method a), was 0.50 tons per day while for method b) (average daily discharge of 31.4 cfs) it was 0.02 tons per day. This further illustrates the errors that may occur if the variability of the flow is not considered and only averages are used in computations. Another effect on determining the variability of the bed load using a discharge relation is the variability of the exponent on the discharge. For the case of Little Granite Creek, the 95% confidence interval on the exponent of 2.89 ranged from 2.68 to 3.10. Therefore, a 5% change in the discharge could be reflected in a 13.4 to 15.5 percent change in the bed load transport.

As discussed above, if the discharge were normalized based on some value, such as 0.8 of bank full, then there is no effect on the percentage change because there is no effect on the exponent. The percentage change is a relative value; the absolute change is the percent times the transport mass for the time period. As an example, consider the Little Granite Creek bed load transport. The percentage change of 5% in discharge resulting in 14.4% change in transport will in absolute terms be equal to a reduction of about 0.7 tons per day if the initial discharge is at 212 cfs (the $Q_{1.5}$ discharge rate). If the flow is at the average daily discharge rate of 31.4 cfs, the absolute reduction is about 0.003 tons per day. Therefore, it is important to not only know the percentage reductions, but the absolute reductions as well. To find both requires an estimate of the bed load and discharge equation. A reasonable estimate of the bed load transport relationship at a site is required. Weinhold (2001) has demonstrated that the P-K method, when calibrated,

gives a good very good estimate of the bed load transport at Little Granite Creek. The comparisons by Lopes et al. (2001) and Habersack and Laronne (2002) also show that the P-K method can give a reasonable estimate of the bed load transport relationship, if the appropriate parameters are selected. The question remains as to whether or not the P-K method, or any other method, reflects the relationship between bed load and discharge found in the data. The applications of two selected methods to the data sets are intended to help answer that question.

Application of P-K and Yang Methods to the Study Sites

Little Granite Creek

P-K Method

Weinhold (2001) has calibrated the P-K method applying the SEDCOMP model to the Little Granite Creek data; therefore, the approach he used will not be reapplied in this study. A further application of the P-K method to the Little Granite Creek data was conducted and is reported on in following section. An important finding from Weinhold was that for the entire data set

$$\tau^*_{r50} = 0.0680\ Q^{0.302} \qquad (R^2 = 0.925) \qquad (24)$$

and exp (see equation (1)) was 0.973.

Yang Method

The Yang method was applied to the Little Granite Creek data. In the application, the entire width of channel at time of sampling was used, i.e., the fine division of a cross section into individual flow slices was not applied. The bed material grain size distribution for the sub-pavement was used to coincide with choice made by Weinhold (2001), although he did not list the sizes he used. The sub-pavement (subsurface) grain size distribution was developed based on a numerical compositing of data from Ryan and Emmett (2002) as shown in Table 2. The maximum size for analysis was chosen as 75 mm to correspond to the bed load sampling techniques (maximum inlet size) employed at the site.

There is very little material in the sand size range in the subsurface. However, there is enough to necessitate use of the Yang sand transport equation (Yang, 1984) which is similar to equation (9). The Yang sand equation is

$$\begin{aligned} \text{Log } C_{ts} &= 5.435 - 0.286 \log(\omega D/\nu) - 0.457 \log(U_*/\omega) \\ &+ [1.799 - 0.409 \log(\omega D/\nu) - 0.314 \log(U_*/\omega)] \log [(VS/\omega) - (V_{cr}S/\omega)] \end{aligned} \qquad (25)$$

where C_{ts} is total sand concentration in parts per million by weight and all the other variables are defined as in equation (9). Equations (9) and (25) must be used in conjunction with one another for particle mixtures ranging from sand to gravel.

Table 2. Distribution of Subsurface Particle Sizes used in Modeling Bed Load Transport, Little Granite Creek.

Classes	Sizes Minimum	Maximum	Geometric Mean	% in Class
Very Fine Sand	0.063	0.125	0.09	0
Fine Sand	0.125	0.25	0.18	0
Medium Sand	0.25	0.5	0.35	0
Coarse Sand	0.5	1	0.71	6
Very Coarse Sand	1	2	1.41	7
Very Fine Gravel	2	4	2.83	7
Fine Gravel	4	8	5.66	12
Medium Gravel	8	16	11.31	16
Coarse Gravel	16	32	22.63	24
Very Coarse Gravel	32	64	45.25	25
Small Cobbles	64	75	69.28	3

The Yang sand and gravel equations were programmed in FORTRAN and the resulting model was applied to the Little Granite Creek data. The measured discharge at the time of the bed load sampling was used to estimate the depth of flow. The measured width was used along with the depth to calculate the average flow velocity from the measured discharge. A water surface slope of 0.020 and a kinematic viscosity of 1.40×10^{-5} ft^2/sec (at 50° F) were fixed for the computations. If the value of the term VS/ω was less than the value of the term $V_{cr}S/\omega$, then no transport was assumed to occur (measured dimensionless stream power less than critical dimensionless stream power for particle size D_i). Although the correlation between the predicted and measured values was 0.736, the Yang method severely over-predicts the bed load. Because the Yang method will predict the same bed load for a given set of particle sizes at a given flow and set of hydraulic characteristics, it will not reflect the variation one finds in the measured bed load at the same discharge. The results from the Yang method were regressed against the measured discharge with the resulting equation of

$$Q_b = 0.172\ Q^{1.64} \qquad (R^2 = 0.996) \qquad (26)$$

where Q_b is in tons per day and Q is in cfs. This relationship is based on the 280 predicted and measured bed loads supplied by Weinhold. Of note in equation (26) is the exponent on Q of 1.64. This is considerable less than the 2.89 found with the measured data and is more on the order of what one would find for suspended load rather than bed load relationships. It is comparable with what Yang (1972) found for his sand based transport equation as a function of stream power.

Based on the poor performance of the Yang method for estimating bed load in a coarse bed mountain stream, the method is not recommended for application until it has been tested further and adjusted to better match field data. The method as originally developed (Yang, 1984) did not include data from a diverse set of coarse bed mountain streams, which has obviously limited its applicability.

East St. Louis Creek

P-K Method

The P-K method was applied to ESLC in order to see how well it could reflect the measured bed load. No attempt was made to calibrate the P-K parameters to the data. That will be left to another study. Instead, the method was applied as directly as possible to determine the relationship between bed load transport and discharge. The P-K method was programmed following the guidance supplied by the SEDCOMP program. The measured data supplied to the study by the US Forest Service formed the basis for the input and comparison information. The discharge, depth and velocity were used to calculate width. Bed load transport rates in kg/sec were converted to tons per day. The fps system of units was used in the computations. Three approaches were investigated. The first followed Weinhold (2001) in that the τ^*_{r50} value was estimated from equation (2) using a b parameter of 0.354 (see equation (19)) from which the a parameter was estimated from the data shown in Figure 1 as 0.055. The value of τ^*_{r50} was allowed to vary with flow in the first approach. The Little Granite Creek exp value (see equation (1)) of 0.973 was used in this first approach. The second approach used the values from Oak Creek of $\tau^*_{r50} = 0.0876$ and exp of 0.982. In the third approach, the Oak Creek parameters were again used, but the bed material supply distribution was modified. The bed material information supplied to the study yielded the following information

Table 3. Distribution of Bed Material Sizes used in Modeling Bed Load Transport, East St. Louis Creek.

Classes	Sizes Minimum	Maximum	Geometric Mean	% in Class
Very Fine Sand	0.063	0.125	0.09	0
Fine Sand	0.125	0.25	0.18	0
Medium Sand	0.25	0.5	0.35	0
Coarse Sand	0.5	1	0.71	0
Very Coarse Sand	1	2	1.41	3
Very Fine Gravel	2	4	2.83	1
Fine Gravel	4	8	5.66	4
Medium Gravel	8	16	11.31	10
Coarse Gravel	16	32	22.63	18
Very Coarse Gravel	32	64	45.25	22
Small Cobbles	64	128	90.51	16
Cobbles +	128	512	256	19

In the third approach, the bed material size distribution was truncated at 75 mm to match the maximum size able to be caught in the sampling equipment, as was done in the previous example for Yang, and the percentages in classes were adjusted. The results of all three approaches were horrendous. In all three, the predicted bed load transport in tons per day was several orders of magnitude higher than the measured bed load. The correlations between the predicted and measured bed loads were poor, and in fact the

correlation for the first approach was negative. Relationships of the form of equation (21) were developed for the results of all three approaches, and all three had exponents much less than 1.5, i.e., in the range expected for suspended sediment relationships and nowhere near the 2.68 as found from the measured data.

The model code was compared with that of SEDCOMP and the computations were also performed in a spreadsheet as a check. No errors in coding or computation were found. A major difference between the approaches used here in applying the P-K method and as applied by Weinhold (2001) or Bakke et al. (1999) is the use of a single stream width. However, it is difficult to understand how dividing a stream section, particularly one that is about 10 feet wide, into multiple sections will reduce the huge discrepancy between the predicted and measured values. The results of the application of the P-K method to the East St. Louis Creek data were very disappointing.

Little Granite Creek Revisited

The results of the P-K applications to East St. Louis Creek prompted the reexamination of the Little Granite Creek data. The P-K method was applied to the Little Granite Creek data using the particle size distribution from Table 1, the entire channel width as the transport section (no subdividing of the section), and the parameters found by Weinhold (2001) as reported previously. The results of the application were disappointing. In the case of Little Granite Creek, the P-K method under-predicted the bed load transport by orders of magnitude, in contrast to the over-predictions for the East St. Louis Creek applications. Although the correlation between the predicated and measured transports rates was much better ($r = 0.691$) than that found for ESLC, the magnitudes of the loads were very different. More important was whether or not the P-K method reflected the relationship between bed load and discharge as evidenced by the measured data. Unfortunately, it did not as it did not for the ESLC applications. The predicted bed loads were modeled with the measured flows (280 values) to yield

$$Q_b = 0.00157\ Q^{0.905} \qquad (R^2 = 0.994) \qquad (27)$$

where Q_b is in tons per day and Q is in cfs. Although the correlation is excellent, the equation is not reflective of the one derived from the measured data (see equation (16)). This difference may be caused by the way the P-K method was applied to the data; however, one would expect the method to be robust enough to generate information that reflected the observed data as long as reasonable parameters and input data were employed. The fact that the measured and predicted bed loads were correlated implies that the method as applied could be adjusted to better fit the data.

The sensitivity of the P-K method was then examined in a manner similar to that done for equation (16). The model parameters found by Weinhold (2001) and used in the above comparison were employed to generate a base condition annual bed load yield from the daily discharge record for Water Year 1988 at Little Granite Creek. WY 1988 contained a peak flow of 202 cfs, very close to the estimate $Q_{1.5}$ discharge of 212 cfs. The hydraulic information was estimated from equations (12) and (13) and the bed material

size distribution from Table 2 was employed. These are all reasonable inputs to the method, so the outcome was expected to reflect the sensitivity in the model. The daily discharges were systematically varied across a range of from 0.8 to 1.2 times the measured values. At each set of discharges, the P-K method was applied and the total annual bed load for the year was determined from the sum of the daily bed loads. The fractional change in bed load was regressed with the fractional change in discharge with the result of

$$\Delta G_b t = 0.951\ \Delta Q \qquad (28)$$

where $\Delta G_b t$ is the fractional change in the annual total bed load relative to a base level and ΔQ is the fractional change in the daily discharge relative to a base level. A zero-intercept model was selected because zero change from base level discharge should equal zero change in base level annual bed load. A regression model with an intercept was investigated also, but the intercept was not significant at the p=0.01 level. The R^2 values for both models were greater than 0.999.

The coefficient in equation (28) can be compared with the exponent on Q in equation (27) of 0.905 derived from the flows measured with the bed load samples. Although very close, a more appropriate comparison is with the power equation developed from the WY 1988 flows (366 values). The resulting equation is

$$Q_b = 0.00121\ Q^{0.962} \qquad (R^2 = 0.9999) \qquad (29)$$

where Q_b is in tons per day and Q is in cfs.

The coefficient in equation (28) and exponent in equation (29) are essentially the same. This confirms the assumption that the sensitivity of the model should be equivalent to the sensitivity of a bed load and discharge power equation derived from model generated information. Conversely, a bed load and discharge power equation derived from model generated information needs to reflect the relationship as derived from field data.

Mark Weinhold (personal communication) was contacted with regards to the large differences between the single channel and subdivided channel computations. He related that it was recognized that a difference existed when applying the P-K method to a single, undivided cross section. He also supplied another set of pavement, sub-pavement and Woman pebble count data (personal communication). The bed material size distribution provided by Weinhold for the sub-pavement was coarser, i.e., greater percentage of larger sizes, than what was used in the modeling described above. The greater fraction of larger sized material had the effect of further reducing the computed bed load transport and made the under-prediction even worse, as expected. Clearly, the differences between the P-K method computations and the measured data could not be explained by the slight differences in the modeled bed material sizes.

Discussion

Bed load discharge is directly related to water discharge because water discharge creates the energy conditions that transport sediment. This relationship between bed load and discharge can be formulated in conceptual models or it can be derived from a regression analysis of measured data. The relationship derived from the measured data is often of the form of equation (15), however other forms are possible. Simple calculus applied to equations of the form of equation (15) shows that the exponent on discharge is a multiplier that magnifies any change in discharge. As was demonstrated by example, a 5% change in discharge for Little Granite Creek should result in a 14.4% change in bed load transport. This was demonstrated from the calculus of the relationship and also by exploring systematic variations in flow as shown in Figure 2. The percentage change in transport is necessary, but not sufficient, to understand the absolute change in transport, that requires an estimate of the transport rate as well. If existing data are available, then a regression relationship such as equation (15) can be developed and the percent and absolute changes in bed load can be estimated. Unfortunately, most sites do not have data available from which a regression relationship can be developed. It may be possible, however, to use a conceptual model (method) of bed load transport as a surrogate for the "real" data. The model can then be used to investigate the sensitivity of its bed load estimates to changes in the flow. However, the model should reflect the type of relationship between bed load transport and discharge as found in previous studies and exemplified by equation (16) for Little Granite Creek. If the model does not, then it will not reflect the same sensitivity to discharge changes as found in the field data.

Unfortunately, the two methods selected for this study, the Parker-Klingeman and Yang, when applied to the study sites, did not reflect the relationship between bed load and discharge as derived from the data. Therefore, use of models, even if carefully calibrated to field data, to examine changes in bed load with changes in discharge is cautioned against until the models realistically represent the types of relationships observed in the field. For many sites, the exponent on the discharge term is usually greater than 2.0. If a relationship derived from model information is less than 2.0, as was the case in the application of the methods in this study, then caution is advised for use in sensitivity analysis.

The results from the application of the P-K method to both the study sites were of particular concern because it has been successfully used to model bed load transport at a number of sites. A more precise and detailed approach should result in a better match with the observed data. Although it is expected that the simple application approach used in this study may have lead to a mismatch between measured and predicted values, the simplifications do not impact the overall performance of the method in matching the sensitivity of the bed load to flow.

Summary and Conclusions

The goal of this study was to develop an equation set or nomograph that predicts the level of flow allowable for various channel configurations of width, depth, slope and

roughness. As this study progressed, it became apparent that the goal could only be reached in a limited sense. The journey to that conclusion is detailed in the body of the report. To arrive at that conclusion required several steps.

Data were supplied for two different sites, Little Granite Creek in Wyoming and East St. Louis Creek in Colorado, and analyzed to provide information for use in the study. Simple calculus applied to the commonly used relationship between bed load transport and discharge showed that the exponent on the discharge term was directly related to fractional changes in bed load transport. This information can be used in estimating the level of change that can be incurred in stream flow before a significant change in bed load transport occurs. This sensitivity of transport to water discharge was demonstrated with an example using the relationship derived from the Little Granite Creek data. In addition to regression equations being developed to model transport, two different conceptual methods were applied to the data, the Parker-Klingeman bed load equation and the Yang gravel transport equation. A basic assumption underlying this effort was that the P-K method, or perhaps the Yang, would adequately reflect the relationship between bed load transport and discharge observed in the field. Neither method was found to match the relationship. The Yang model was deemed unsuitable for further consideration because it was developed from data sets that did not reflect the conditions encountered in coarse bed streams. Its application to one of the data sets demonstrated its limitations. Although the P-K method had been successfully applied in an earlier study to estimate bed load at one of the sites used in this study, it did not perform well when applied here to the data sets. The P-K model was investigated further by using actual flow data, and parameters from the earlier application or developed in this study, to generate bed loads for a suite of changing flow conditions. The results did not compare well with the types of relationships found at many sites. Therefore, use of any model, other than regression models derived from field data, to estimate the sensitivity of bed load transport to changes in discharge is strongly cautioned against unless the model can be shown to adequately portray the bed load-discharge relationship as observed in the field. Until models can be shown to adequately reflect this relationship, then sensitivity analysis must rely on equations developed form observed data. Future study should focus on why the Parker-Klingeman method did not reflect the sensitivity of bed load transport to discharge as seen in the field data.

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* Note – manuscript found on Dr. Parker's website at http://www.ce.umn.edu/~parker/